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Identification of yrast high-K isomers in ^{177}Lu and characterisation of ^{177m}Lu

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Abstract

Long-lived high-K states have been identified in ^{177}Lu, including an isomer with $\tau > 10$ μs, placed at 3530 keV and associated with the yrast $K^\pi = 39/2^-$, 5-quasiparticle state predicted in multi-quasiparticle-state calculations. The γ-decay of the isomer exposes the rotational band based on the 160-day $23/2^-$ isomer, ^{177m}Lu, with band properties which support its proposed configuration. A 90-ns isomer at 1325 keV is associated with the predicted 3-quasiparticle $K^\pi = 25/2^+$ state while a 5-quasiparticle $33/2^+$, 902-ns isomer with highly-hindered decays is identified at 2771 keV. Both exhibit rotational bands whose properties are used to support the assigned configurations. The possibility that the $K^\pi = 39/2^-$ isomer found in this work should be identified with a β-decaying isomer, proposed recently to populate the 51-min $37/2^-$ isomer in ^{177}Hf, is discussed in terms of the implied log ft values, configuration changes, and hindrances for K-forbidden γ-decays.

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Recent studies have shown the efficacy of inelastic and deep-inelastic reactions with heavy-ion beams for the population and identification of high-spin isomers in nuclei near stability, nuclei which are generally inaccessible through fusion–evaporation reactions [1]. Near the line of stability, high-spin isomers abound in lutetium and hafnium nuclei due to the presence close to the Fermi surface of neutrons and protons with relatively high projections (Ω) of the particle angular momentum on the nuclear deformation axis. In multi-quasiparticle states such projections can be summed to

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produce high-K states at relatively low excitation energies. One consequence is the possibility of hindered transitions due both to low transition energies and the difficulty of making the large changes in K required to reach lower-lying states [2]. A noteworthy example is the $K^\pi = 23/2^-$ state at 970 keV in ^{177}Lu which has a 160-day half-life, a 78% β-decay branch to the $K^\pi = 23/2^+$ isomeric state in ^{177}Hf ($\log ft = 6.4$) and a 22% E3 γ-ray branch to the $17/2^+$ member of the $7/2^+$ [404] band within ^{177}Lu [3].

The 3-quasiparticle Nilsson configuration assigned [4] to the $23/2^-$ isomer,

$$\nu 7/2^-[514]9/2^+[624] \otimes \pi 7/2^+[404],$$

was supported by several early magnetic moment measurements [5,6], with more recent studies resulting (as reviewed in [3]) in a value of $\mu = 2.320(14)$ n.m. This translates to a g-factor of 0.20, consistent with the value of $+0.22$ expected for the proposed $\nu^2\pi$ combination. The spectroscopic quadrupole moment evaluated from several measurements is reported [3] as 5.70(8) eb.

Independent confirmation of the configuration of the $23/2^-$ isomer can be obtained through the properties of its associated rotational band. A $25/2^-$ rotational state was tentatively assigned at 1243(5) keV in early (d, p) studies [7] and band members up to a $29/2^-$ state have recently been firmly identified using γ-ray spectroscopy and ^{7}Li-induced incomplete-fusion reactions [8]. Multi-quasiparticle-state calculations carried out with the approach described by Jain et al. [9] but with the inclusion of a Lipkin–Nogami treatment of the pairing correlations (see, for example Refs. [10,11]) reproduce the excitation energy of the $23/2^-$ isomer, and also predict the presence of a $K^\pi = 39/2^-$ 5-quasiparticle state at about 3400 keV [8]. This is favoured in energy and is thus likely to lead to a higher-lying isomer. The predicted state has a configuration related to that of the $23/2^-$ isomer by an additional 2-proton excitation, namely:

$$\nu 7/2^-[514]9/2^+[624]$$
$$\otimes \pi 7/2^+[404]7/2^-[523]9/2^-[514].$$

Such high spins cannot be populated in the incomplete fusion reactions referred to above. However, Al-Garni et al. [12] have recently reported the observation of γ-rays from the well-known $K^\pi = 37/2^-$, 51-min isomer at 2740 keV in ^{177}Hf which they attributed to indirect population through β-decay from a previously unknown high-K isomer in ^{177}Lu. The activity was extracted from a thermal ion-source following production in deep-inelastic collisions with ^{136}Xe beams at energies of 11.5 MeV per nucleon. A 6(3)-min half-life was deduced from the growth curve for the decay of the 51-min Hf isomer, but no γ-rays within ^{177}Lu were identified. Hence both the identification and association with the predicted state in ^{177}Lu are uncertain, and importantly, the excitation energy and, therefore, decay widths are unknown.

In this Letter we report the identification of a $K^\pi = 25/2^+$ 3-quasiparticle isomer, a $K^\pi = 33/2^+$ 5-quasiparticle isomer and a long-lived isomer (mean-life > 10 µs) which we associate with the predicted $K^\pi = 39/2^-$ state. This last isomer γ-decays predominantly through the $23/2^-$ isomer band. The properties of this band and those associated with the other isomers are used to test the configurations of the $23/2^-$, $25/2^+$ and $33/2^+$ intrinsic states. With the identification of the energy and γ-decays of the $39/2^-$ isomer, the proposition that it could also be the source of the 6-min β-decay half-life observed by Al-Garni et al. [12], is examined, in terms of limits on the β and γ branching ratios and the consequent $\log ft$ of the purported β-decay branch.

Following new spectroscopic information on isomers and band structures in the nuclei ^{175}Lu, ^{176}Lu and ^{177}Lu that has become available through studies of Li-induced reactions [8,11], we have carried out measurements aimed at the identification of high-spin states in these and neighbouring nuclei. The experiments used 6.0 MeV per nucleon ^{136}Xe beams provided by the ATLAS Facility at Argonne National Laboratory. Nanosecond pulses, separated by about 825 ns, were incident on targets of natural Lu (97% ^{175}Lu, 2.6% ^{176}Lu), Lu enriched to 47% in ^{176}Lu, and enriched ^{174}Yb. The targets were approximately 6 mg/cm^2 in thickness with 25 mg/cm^2 Au foils directly behind. The beam conditions (~ 24% above the Coulomb barrier) should result in inelastic processes well above the barrier with transfer of nucleons between target and projectile, and inelastic excitation of the target nuclei. Closer to the barrier, near the rear of the primary foils, some proportion of single nucleon transfer would be expected.

Gamma-rays were detected in the gammasphere array [13] with 96 escape-suppressed Ge detectors in operation. About 3×10^8, 2×10^9 and 2×10^8 coincidence events of fold-three and higher were collected for the ^{175}Lu, ^{176}Lu and ^{174}Yb targets, respectively. Recent developments in software [14] allowed the efficient production of γ-ray coincidence matrices with different time and energy gating conditions. With the resulting flexibility, a variety of time conditions relating both the time difference between specific γ-rays, and their time relative to the beam pulses was available. In particular, decays from isomers were isolated by selecting events only between beam pulses. A large number of known isomers in the Yb, Lu, Hf, Ta and W nuclei were observed and comparison of their yields for the different targets provided an initial basis for assignment of new structures, some of which cannot be directly assigned to a specific isotope because of the very long lifetimes of the isomers which intervene between such structures and known states. This is obviously the case for the 160-day, $23/2^-$ isomer in ^{177}Lu. However as indicated above, recent studies [8] have identified cascade and cross-over transitions from the first few states above this isomer.

Fig. 1 shows gamma-ray spectra, obtained with the ^{176}Lu target, of a sequence of transitions following the decay of a long-lived isomer, with branches of 619 and 227 keV feeding the upper states of a rotational band, apparently isolated from other structures. The coincidence spectra were produced by double-gating on the 619/727 keV combination and the 227/765 keV pair, thus selecting the parallel paths through the two signatures of the band. The lowest transitions in the band match those assigned by McGoram et al. [8], Lu X-rays are observed in coincidence, and the cross-comparison of isotope yields support placement of the

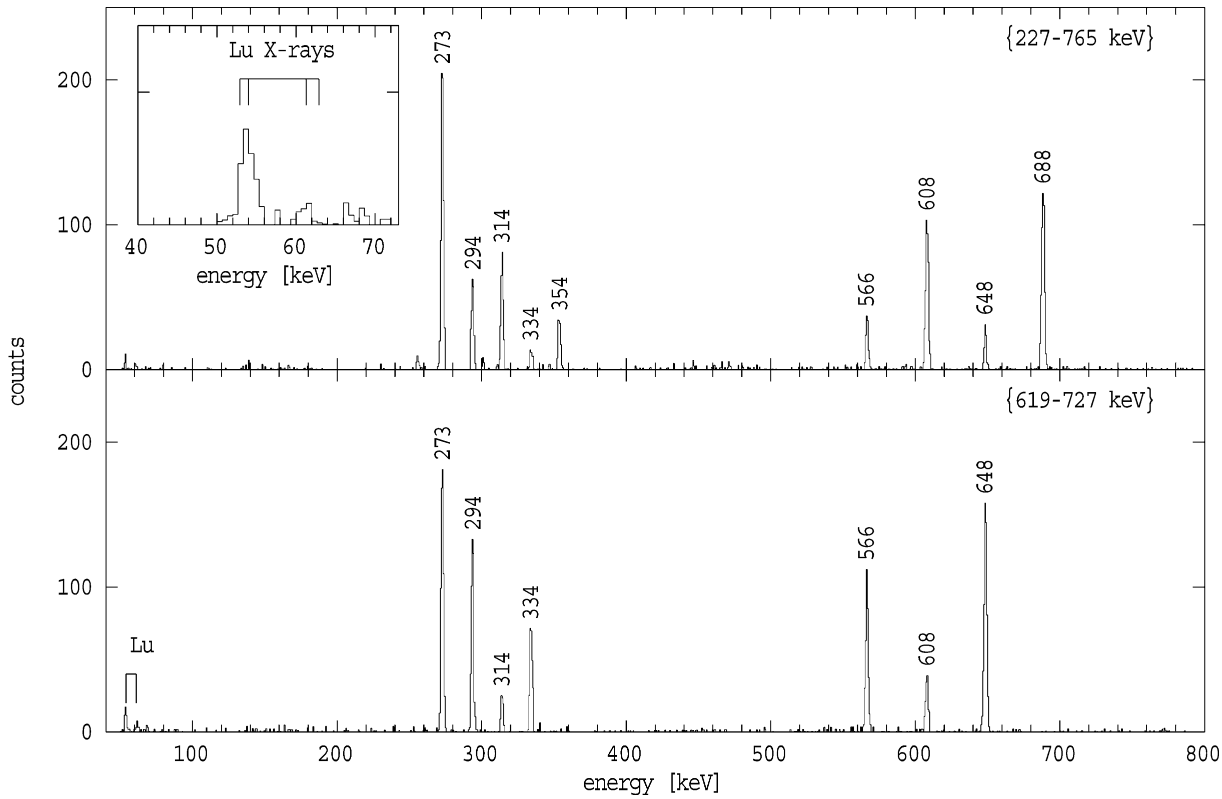

Fig. 1. Triple coincidence spectra in the out-of-beam time period, with gates on transitions following the decay of the $39/2^-$ isomer in ^{177}Lu as indicated. The inset shows a detail in the X-ray energy region of the sum of several spectra with double coincidence gates within the band. The continuous Compton background has been subtracted.

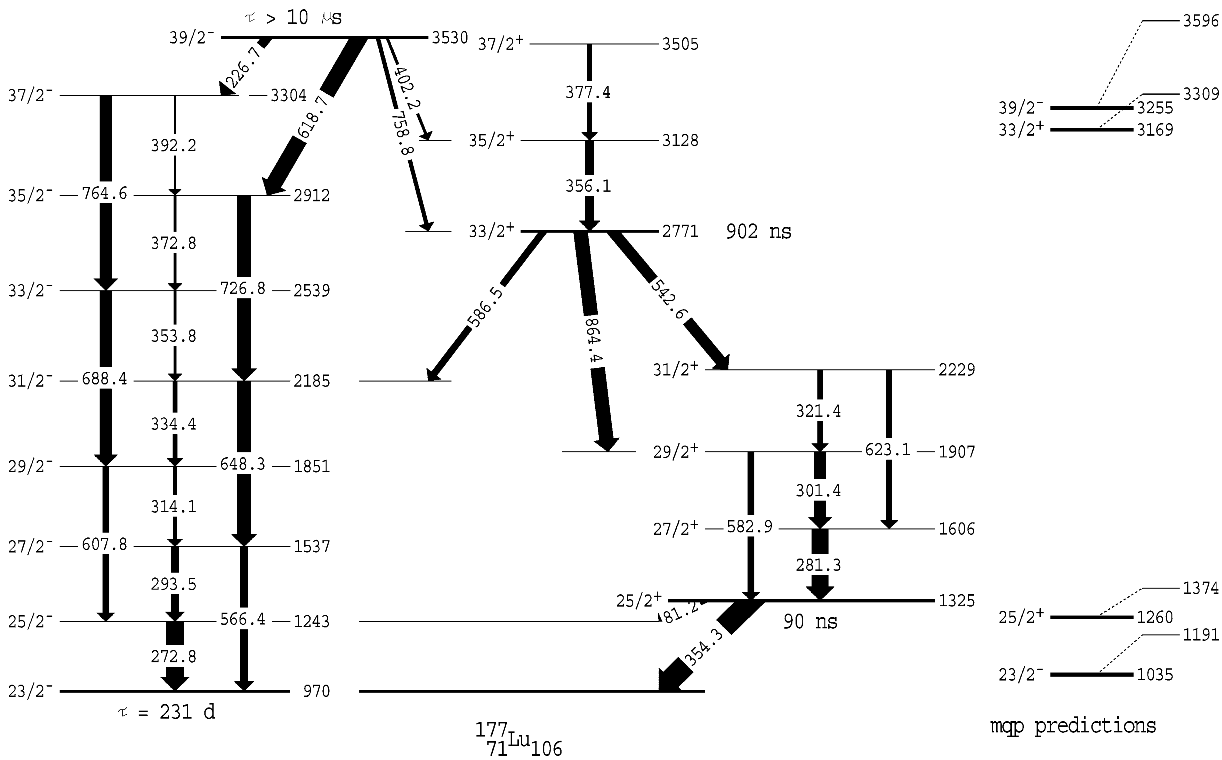

Fig. 2. Partial level scheme showing the proposed decay of the $39/2^-$, $33/2^+$ and $25/2^+$ isomers in ^{177}Lu. (Previous work [8] had assigned the $23/2^-$ band up to the $29/2^-$ state and also had evidence for the $25/2^+$ isomer.) Intrinsic state energies from multi-quasiparticle-state calculations [8] are given on the right (labelled mqp), with and without residual interactions (thick and narrow lines, respectively).

band as feeding ^{177m}Lu. The new isomer is placed at 3530 keV. A total conversion coefficient of $\alpha_T = 0.32(6)$ is obtained from intensity balances for the 227 keV transition connecting the isomer to the $37/2^-$ member of the $23/2^-$ band, consistent with an M1 multipolarity and the $39/2^-$ assignment. The lifetime of the isomer, however, is outside the range of the present measurements and we place a limit of $\tau >$ 10 μs on its value.

Fig. 2 shows the proposed level scheme based on these and other considerations. Two other isomers are observed. The 1325 keV level has a mean-life of 90(5) ns and decays predominantly via the 354 keV transition and also by an 81 keV transition to the first excited state of the $23/2^-$ band. From its total conversion coefficient, the 81 keV transition is of E1 multipolarity. This leads to the proposed $25/2^+$ assignment and directly links the structure into ^{177}Lu. The band structure above is populated from a higher lying isomer placed at 2771 keV with decays to both the $23/2^-$ and $25/2^+$ bands as indicated. Its lifetime is longer and was deduced from intensities of the (double-gated) transitions with respect to the beam pulsing as $\tau_m = 902(90)$ ns.

Fig. 3(a) shows a spectrum coincidence-gated on both the 586 keV connecting transition and the 648 keV transition within the proposed $23/2^-$ band, indicating the presence of the isomer at 2771 keV. The band structure above the $25/2^+$ isomer is clear in the time-delayed 354 keV-gated spectrum given in Fig. 3(b). A prompt double-gate on the 543 keV connection from the 2771 keV isomer and the 623 keV in-band transition given in Fig. 3(c) shows the 354 keV transition placed at the base of the 90-ns isomer, and the first transition (273 keV) of the $23/2^-$ band, reduced in intensity compared to the 281 keV in-band transition because of the (relatively short) $25/2^+$ isomer lifetime. A delayed gate on the 864 keV transition

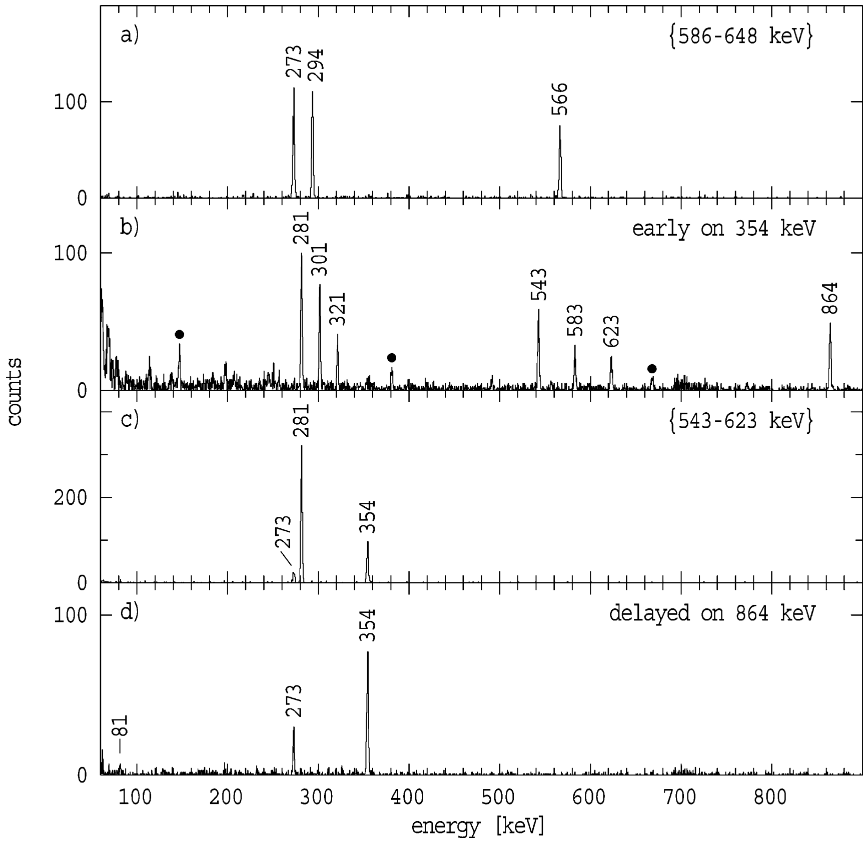

Fig. 3. Coincidence spectra with (a) prompt, double gate on the 586 and 648 keV transitions (b) transitions preceding in time, the 354 keV decay from the 90-ns isomer, (c) prompt, double gate on the 543 and 623 keV transitions, and (d) transitions delayed with respect to the 864 keV transition. All spectra are taken in the out-of-beam region. Contaminants are indicated by filled circles.

(Fig. 3(d)) clearly shows the decay of that isomer, including the 81 keV transition connecting it to the first member of the $23/2^-$ band.

The branching pattern (and associated hindrances for the transitions from the 2771 keV isomer) favour a $33/2^+$ assignment although multipolarities were not measured directly. The lifetime is relatively long which reduces the efficiency for observing transitions which precede this isomer, but several have been identified in time correlations and, importantly, in the time between beam pulses, indicating population from a higher isomer again. Two of the transitions are interpreted as cascades within the band based on the $33/2^+$ isomer while the 759 keV transition matches the energy expected for a link to the $39/2^-$ isomer at 3530 keV. The 402 keV transition is tentatively placed as connecting the same isomer to the first state of the $33/2^+$ rotational band. This is consistent with the intensity balance and other data but there remains a small mismatch in energy, hence the tentative assignment. Delayed population of the 3505 keV member of the $33/2^+$ band is presumably through a low energy transition which has not been observed directly.

We turn now to the properties of the bands revealed in the decay of the isomers. In-band branching ratios are listed in Table 1. Using the rotational model, the values of the ratio $(g_K - g_R)/Q_0$ can be extracted from the ratio of γ-ray intensities of $\Delta J = 2$ and $\Delta J = 1$ transitions (λ) and using the known intrinsic quadrupole moment Q_0, the values of $g_K - g_R$ can be deduced.

The average value of $|g_K - g_R| = 0.105(5)$ obtained for the $23/2^-$ band is in agreement with the value of $-0.073(23)$ expected (assuming $g_R =$

Table 1
In-band branching ratios and $|g_K - g_R|$ values for states of the proposed $23/2^-$ and $25/2^+$ bands in ^{177}Lu

J^π	$E_\gamma(\Delta J = 1)$ (keV)	$E_\gamma(\Delta J = 2)$ (keV)	λ	$\lvert g_K - g_R\rvert$ exp.[1]	$g_K - g_R$ theory[2]
$K^\pi = 23/2^-$					−0.073
$37/2^-$	392.2	764.6	8.7(15)	0.055(35)	
$35/2^-$	372.8	726.8	4.86(77)	0.119(25)	
$33/3^-$	353.8	688.4	4.26(34)	0.099(13)	
$31/2^-$	334.4	648.3	2.84(16)	0.111(8)	
$29/2^-$	314.1	607.8	1.73(13)	0.119(12)	
$27/2^-$	293.5	566.4	1.99(6)	0.090(10)	
$K^\pi = 25/2^+$					+0.16
$31/2^+$	321.4	623.1	0.83(9)	0.208(17)	
$29/2^+$	301.4	582.9	0.42(4)	0.200(14)	

[1] Taking $Q_0 = 7.32$ eb.
[2] Assuming $g_R = +0.30$.

+0.30) for the predicted 3-quasiparticle configuration

$$\nu 7/2^-[514]9/2^+[624] \otimes \pi 7/2^+[404],$$

and it is essentially the same as the measured value (0.09(3)) for the corresponding $23/2^-$ band in the isotone ^{179}Ta [15]. (The error on the expected value includes the errors on each component orbital for which empirical values have been used, but not the systematic uncertainty in g_R.) The other yrast multi-quasiparticle states predicted are indicated on the right of Fig. 2. (The energies given there are shown with and without inclusion of the residual interactions estimated from empirical two-particle spin–spin interactions as described in Ref. [16].) The $K^\pi = 25/2^+$ state has the configuration:

$$\nu 7/2^-[514]9/2^+[624] \otimes \pi 9/2^-[514], \qquad (1)$$

for which a value of $g_K - g_R = +0.16(2)$ is expected, compared to an experimental value of $|g_K - g_R| = 0.20(2)$. This is reasonable agreement given the uncertainty in the component g_Ω values and the possible configuration-dependent differences associated with g_R. It is also in good agreement with the experimental value of 0.23(2) measured for the $25/2^+$ band in ^{179}Ta [15].

The similarities between the ^{177}Lu bands and those in ^{179}Ta are clear in the comparison of alignments shown in Fig. 4. Note that these should be similar, but not necessarily identical since a common reference has been used, whereas the deformations may be slightly different, and there is also a marginal difference expected in the rotational properties of the constituent orbitals, especially those for the $9/2^+[624]$ neutron.

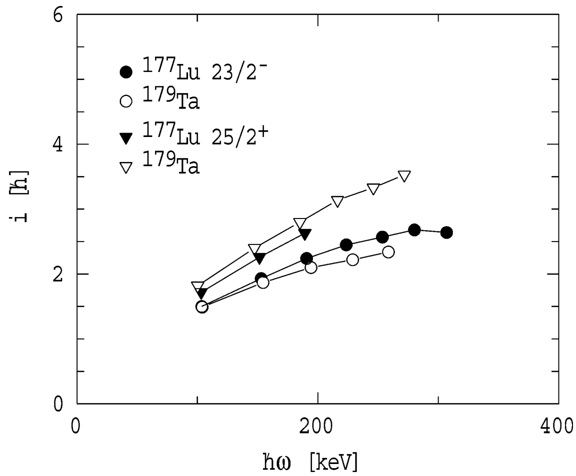

Fig. 4. Comparison of alignments of the proposed $23/2^-$ and $25/2^+$ bands in ^{177}Lu and ^{179}Ta, extracted using a common reference.

The energy of the yrast $33/2^+$ state from the 5-quasiparticle configuration

$$\nu 7/2^-[514]9/2^+[624]$$
$$\otimes \pi 7/2^+[404]9/2^-[514]1/2^+[411]$$

is predicted nearly 400 keV higher in energy than the isomeric level observed, in contrast to the situation with the other isomers whose predicted energies tend to be lower than observed, especially after inclusion of residual interactions. This is generally the case since the method used to estimate the residual interactions

Table 2
Mean-lives, branching ratios and hindrances for decays from the isomers in ^{177}Lu

Final state J^π	E_γ (keV)	I_γ relative	$M\lambda$	α_T	Hindrance	ν	f_ν
			$25/2^+$; 1325 keV; 90(5) ns				
$25/2^-$	81.2	18.1(13)	E1	0.609	$0.96(10)\times 10^6$	0	
$25/2^-$	354.3	81.9(39)	E1	0.014	$1.8(2)\times 10^7$	0	
			$33/2^+$; 2771 keV; 902(90) ns				
$31/2^-$	586.5	21.4(22)	E1	0.0045	$2.8(4)\times 10^9$	4	230
$29/2^+$	864.4	44.1(43)	E2	0.0053	$7.2(10)\times 10^4$	2	269
$31/2^+$	542.6	34.5(32)	M1	0.0373	$1.3(2)\times 10^7$	3	238
			$39/2^-$; 3530 keV; > 10 µs				
$35/2^-$	618.7	49.2(46)	E2	0.011	$> 1.5\times 10^5$	6	> 7.3
$37/2^-$	226.7	29.8(23)	M1	0.379	$> 1.4\times 10^7$	7	> 10.5
$33/2^+$	758.8	(13.3(35))	E3	0.017	$> 1.3\times 10^1$	0	
$35/2^+$	402.2	(7.7(16))	M2	0.279	$> 1.1\times 10^3$	1	
			$39/2^-$; 3530 keV; [9(4) min]				
(i) no β-branch	618.7		E2		$7.9(40)\times 10^{12}$	6	141
	226.7		M1		$7.3(37)\times 10^{14}$	7	133
	758.8		E3		$6.9(39)\times 10^8$	0	
	402.2		M2		$5.7(31)\times 10^{10}$	1	
(ii) 85% β-branch	618.7		E2		$5.1(26)\times 10^{13}$	6	193
	226.7		M1		$4.8(24)\times 10^{15}$	7	174
	758.8		E3		$4.5(25)\times 10^9$	0	
	402.2		M2		$3.6(20)\times 10^{11}$	1	

tends to overestimate their magnitude. Nevertheless, the band fragment observed above the isomer is consistent with the proposed assignment, since the energies are almost identical to those of the $K^\pi = 16^+$ isomer band in ^{178}Hf [17] which has essentially the same configuration but without the (spectator) $1/2^+$[411] proton. (Also crossover transitions are not observed, consistent with the expected dominance of cascade transitions for this configuration.)

We now consider the transition strengths and possible β-decay branch from the $39/2^-$ isomer. The γ-decay of the 51-min isomer in ^{177}Hf is strongly observed in the present measurements, with an intensity (as deduced from the double-gated γ-ray spectra), approximately six times stronger than the γ-decay of the newly assigned $39/2^-$ isomer in ^{177}Lu. The observed intensity of the ^{177}Hf band therefore represents an upper limit to the proposed β-decay branch, if indeed that can be attributed to the decay of the $39/2^-$, 3530 keV state. The limit would correspond to an 85% β-branch from that state. This is obviously an upper limit since there may be direct population of the Hf isomer via the deep inelastic or transfer reactions. It is not possible to quantify this precisely in the present experiment, but comparisons of the yields of other isomers (of various spins) in ^{176}Hf, ^{177}Hf and ^{178}Hf suggests that direct population of the 51-min isomer in ^{177}Hf could be significant.

Table 2 gives the transition strengths of the primary γ-decays with the lifetime values measured in the present work for the $33/2^+$ and $25/2^+$ isomers, together with the measured γ-ray branches. Alternative strengths for the decay of the $39/2^-$ isomer are given for the present limit (> 10 µs) and also for the 6(3)-min half-life given in Ref. [12] for the $39/2^-$ isomer, with two extreme values for the β-decay branch. The strengths are given in terms of the hindrance factor $F = \frac{\tau}{\tau_W}$, the ratio of the partial mean-lives to the Weisskopf estimates τ_W, and the reduced hindrances $f_\nu = F^{1/\nu}$, where the degree of forbiddenness for mul-

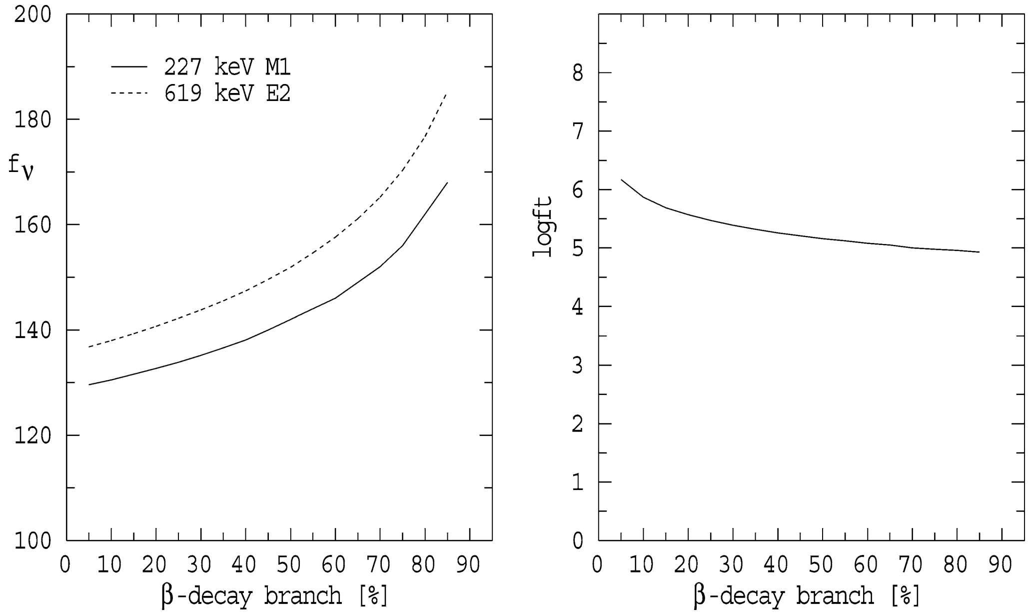

Fig. 5. Reduced hindrances and log ft values as a function of the percentage β-decay branch from the 3530 keV isomer, assuming a half-life of 6-min.

tipolarity λ is given by $\nu = \Delta K - \lambda$. Large reduced hindrances imply relatively pure K values for both initial and final configurations, consistent with expectations for states low in energy with respect to the yrast line and for well-deformed nuclei. Values comparable to those observed for the decay of the $33/2^+$ isomer of f_ν (in the range 100–300) are observed in the decay of isomers in ^{178}Hf and ^{176}Lu [11], with the largest value for E2 transitions in the region being $f_\nu \sim 300$ for the E2 decay of the 6^+ isomer in ^{174}Yb [18].

Although not K-forbidden, both E1 transitions from the $25/2^+$ isomer are retarded by about 10^6, consistent with E1 transition strengths between intrinsic states in this region. The 10 μs lifetime limit for the $39/2^-$ isomer is not directly informative since it corresponds to transition with low reduced hindrances. Transition strengths which were normal ($f_\nu \geqslant 30$) would result in a lifetime in the millisecond region. At the other extreme, if its lifetime were of the order of minutes, the hindrances of its K-forbidden decays would be reasonable, as discussed below.

Two entries are given in the table for the $39/2^-$ isomer corresponding to the limits of a negligible β-decay branch and the maximum branch of 85% deduced earlier. The reduced K-forbidden γ-ray hindrances for decays to the $23/2^-$ band are acceptable for both extremes, but the E3 and M2 transitions connecting the $39/2^-$ and $33/2^+$ isomers are very retarded, only the M2 decay being K-forbidden. This could be a consequence of the specific configuration change corresponding to a $7/2^-[523]$ to $1/2^+[411]$ proton transition; both M2 and E3 transitions are j-forbidden, since the orbitals arise from $h_{11/2}$ and $s_{1/2}/d_{3/2}$ parents, respectively. The excitation energy now measured translates to a β-decay energy, $Q_{\beta-} =$ 1288 keV for the decay of the $39/2^-$ isomer in ^{177}Lu to the $37/2^-$ isomer at 2740 keV in ^{177}Hf. The log ft values deduced using this energy, are shown together with the reduced hindrances in Fig. 5 as a function of the assumed β-decay branch. Both parameters vary only slowly over the range. The proposed $39/2^- \rightarrow 37/2^-$ β-decay branch corresponds to an allowed transition (expected values of log $ft = 4$–7 [19]) and this would be satisfied over essentially the entire range. To put it another way, if the reduced hindrances for the γ-ray branches of the newly identified isomer in ^{177}Lu at 3530 keV exceed values of 100, which is possible given the large hindrances observed both in neighbouring nuclei, and in the same nucleus (e.g., from the $33/2^+$ isomer), the resultant partial lifetimes would be such that a significant β-decay branch could occur. This partly supports the proposition by Al-Garni et al. [12] that their observed 6-min population of the 51-min isomer in ^{177}Hf could arise from the decay of this (now established) 5-quasiparticle $39/2^-$ isomer in ^{177}Lu.

Obviously, direct measurement of the lifetime of the isomer observed here through γ-ray studies, is highly desirable. Observation of a shorter lifetime which would mitigate the possible problem of excessive retardation of transitions to the $33/2^+$ isomer, would necessarily negate any connection with a proposed β-activity, and would then leave open the question of its source.

To summarise, high-K multi-quasiparticle states in ^{177}Lu have been identified using deep-inelastic reactions and γ-ray spectroscopy with gammasphere. The isomeric intrinsic states observed have been characterised through the properties of their associated rotational bands, including the band based on the well-known (230-day mean-life) $23/2^-$ isomer. The results are in reasonable agreement with the predictions of multi-quasiparticle calculations for states that should fall near the yrast line. The K-hindrances for decays from the $33/2^+$ isomer are large and while the limit obtained for the lifetime of the $39/2^-$ isomer is not sufficient to test the question of the validity of the K-quantum number, the state could be sufficiently long-lived to β-decay, as recently proposed, providing transitions to the lower-lying $33/2^+$ intrinsic state were very retarded.

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References

[1] C. Wheldon, R. D'Alarcao, P. Chowdhury, P.M. Walker, E. Seabury, I. Ahmad, M.P. Carpenter, D.M. Cullen, G. Hackman, R.V.F. Janssens, T.L. Khoo, D. Nisius, C.J. Pearson, P. Reiter, Phys. Lett. B 425 (1998) 239.
[2] P.M. Walker, G.D. Dracoulis, Nature 399 (1999) 35.
[3] F.G. Kondev, Nucl. Data Sheets 98 (2003) 801, and references therein.
[4] L. Kristensen, M. Jorgensen, O.B. Nielsen, G. Sidenius, Phys. Lett. 8 (1964) 57.
[5] K.S. Krane, C.E. Olsen, W.A. Steyert, Phys. Rev. C 10 (1974) 825.
[6] E. Schoeters, R.E. Silverans, L. Vanneste, K. Freitag, H. Hubel, Z. Phys. A 272 (1975) 203.
[7] M.M. Minor, R.K. Sheline, E.T. Jurney, Phys. Rev. C 3 (1971) 766.
[8] T.R. McGoram, PhD thesis, Australian National University, 2002, unpublished;
T.R. McGoram, G.D. Dracoulis, T. Kibédi, A.P. Byrne, A.M. Baxter and S.M. Mullins, in preparation.
[9] K. Jain, O. Burglin, G.D. Dracoulis, B. Fabricius, N. Rowley, P.M. Walker, Nucl. Phys. A 591 (1995) 61.
[10] G.D. Dracoulis, S.M. Mullins, A.P. Byrne, F.G. Kondev, T. Kibédi, S. Bayer, G.J. Lane, T.R. McGoram, P.M. Davidson, Phys. Rev. C 58 (1998) 44.
[11] T.R. McGoram, G.D. Dracoulis, T. Kibédi, A.P. Byrne, A.M. Baxter, S.M. Mullins, Phys. Rev. C 62 (2000) 031303.
[12] S. Al-Garni, et al., in: E. Norman, et al. (Eds.), Proceedings of the International Nuclear Physics Conference, INPC2001, Nuclear Physics in the 21st Century, Berkeley, CA, 30 July–3 August, in: American Institute of Physics Conference Proceedings, vol. 610, 2001, p. 854.
[13] R.V.F. Janssens, F.S. Stephens, Nucl. Phys. News 6 (1996) 9.
[14] M. Cromaz, T.J.M. Symons, G.J. Lane, I.Y. Lee, R.W. MacLeod, Nucl. Instrum. Methods Phys. Res. A 462 (2001) 519.
[15] F.G. Kondev, G.D. Dracoulis, A.P. Byrne, T. Kibédi, S. Bayer, Nucl. Phys. A 617 (1997) 91.
[16] K. Jain, P.M. Walker, N. Rowley, Phys. Lett. B 322 (1994) 27.
[17] S.M. Mullins, G.D. Dracoulis, A.P. Byrne, T.R. McGoram, S. Bayer, W.A. Seale, F.G. Kondev, Phys. Lett. B 393 (1997) 279;
S.M. Mullins, G.D. Dracoulis, A.P. Byrne, T.R. McGoram, S. Bayer, W.A. Seale, F.G. Kondev, Phys. Lett. B 400 (1997) 401, Erratum.
[18] A.G. Schmidt, J.W. Mihelich, E.G. Funk, Phys. Rev. C 9 (1974) 2346.
[19] B. Singh, J.L. Rodriguez, S.S.M. Wong, J.K. Tuli, Nucl. Data Sheets 84 (1998) 487.